



## Challenges and solutions for energy systems with high shares of wind energy

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Chapter 9

# Challenges and solutions for energy systems with high shares of wind energy

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Wind energy is becoming a significant player in energy systems, with ever-increasing market shares. 2013 was a record-breaking year for wind in energy systems: in Spain, for instance, wind energy became the top supplier, providing 21.1% of the country's overall electricity demand. In Germany, wind peaked at 59% of electricity demand for some one-hour periods, a performance matched by the US state of Colorado (60%). In Denmark, wind energy provided on average more than 30% of demand during the year, and hit a record of 90 hours during which wind energy production was higher than demand, peaking at an oversupply of 122%<sup>[1]</sup>.

In the light of political targets to further increase the share of renewable energy in power systems, more regions of the world will see increasing average shares of wind power. Even more importantly, we will increasingly see situations of extreme over- or under-supply due to fluctuations in wind power production. This makes the operation of power systems more challenging. In general, power systems need to serve two basic requirements:

1. power should be available on demand; and
2. the voltage delivered to consumers should remain stable.

Power systems were originally designed around large-scale synchronous generators in the form of controllable thermal power plants. Wind power plants (WPPs), however, are asynchronous generators. Integrating large shares of asynchronous generation requires new approaches and solutions <sup>[2]</sup>.

The integration of wind into today's energy systems has three aspects that are separate, though related. The first is network integration. WPPs are typically sited in the best wind locations, which often do not coincide with centres of consumption or the availability of sufficient existing grid capacity. To make best use of wind energy potential, sufficient grid capacity needs to be available to export power, and transmission bottlenecks should be minimised. With increasing shares of wind energy in the system, the existing infrastructure is challenged in some regions, at both medium- and high-voltage levels.

The second aspect relates to long-term and medium-term integration. Wind energy production can be highly variable, depending on the wind resource availability. At times each WPP will generate at maximum capacity, yet on other occasions it will produce nothing. Sufficient alternative generation capacity – or demand response – must therefore be available during times of low or no wind energy production. In the long term, adequate investment incentives must be provided for controllable backup power in order for sufficient capacity to be made available to the market. In the medium term (i.e. day-ahead), the expected ramping up and down by WPPs must be mirrored by sufficiently flexible units that can be dispatched so as to maintain the balance between power production and demand.

The third aspect relates to short-term integration. Here, the forecast errors in wind energy generation lead to mismatches between forecast and actual wind production, and hence to unexpected fluctuations in the power supply. This poses a challenge to system balancing. In the very short term – from seconds to minutes – the power system needs fast control in order to balance demand and supply and so maintain a stable voltage. To make this possible, the system operator requires access to sufficient reserves and other services that are collectively known as ancillary services.

The focus of this chapter is mostly on short-term integration issues and the corresponding need for ancillary services. Here we should remember that policy and regulation influence the need for balancing. Shorter gate-closure times in the power market, for instance, allow better forecasting and create the opportunity to re-dispatch generators before the need for balancing arises. Allowing new actors into the market, especially from the demand side, also helps providing the required services at the lowest possible cost.

### **Balancing energy systems with high shares of wind power**

In power systems, balancing is traditionally done by dedicated power capacity reserves. The details of how control is achieved are different for each

system, depending on the reliability criteria defined for the system, the way reserves are traded in markets, and the extent of trading between neighbouring systems [3].

Wind energy increases the need for balancing because of the wind power forecast error. Unexpected decreases in wind power production have the same effect as unexpected increases in demand. Experience from Europe shows that wind shares of up to 20% may not require additional primary control capacity as long as the wind capacity is geographically distributed over a wide area [2]. However, mismatches between forecast and actual wind power production will eventually have to be handled through balancing, and in particular via the secondary control capacity.

The largest challenges in integrating wind energy typically arise in situations which combine high wind production, low demand, limited or inflexible trade with neighbouring power systems, and low flexibility in the power plants that are operating or otherwise available [3].

So what can be done to balance energy systems with very high shares of wind? There are five main options:

1. Well-integrated grids with good interconnections reduce balancing needs. Geographically large balancing areas decrease the need for balancing by evening out deviations in both demand and wind production. Increasing the geographical areas from which control capacity (reserves markets) can be obtained will decrease the costs of system operation, since it makes lower-cost options more accessible.
2. Good interconnections with the heat sector will reduce balancing needs in the power system. With combined heat and power (CHP) units as well as electrical boilers and heat pumps linking the heat and power sectors, the heat system can be used to counterbalance fluctuations on the power side, especially when heat storage is abundant.

3. Demand response will reduce balancing needs on the supply side.

4. Large-scale electricity storage can provide additional control capacity that could replace the need for flexible thermal power generation. The prospect of a large fleet of electric cars and an increasing share of heat pumps for domestic heating could be especially important in this respect.

5. WPPs themselves can deliver some ancillary services.

The large-scale integration of wind power into power systems will require us to find integrated regulation strategies for the whole energy system – a process that is likely to require all the options mentioned above. Wind power plants will have to play a role not only in producing energy, but also in delivering ancillary services. The following sections address this in more detail.

### Ancillary services

This section provides an overview of the need for ancillary services in power systems, how this is affected by increased wind power penetration, and the potential for WPPs to provide these services.

The purpose of ancillary services from power generating units is to ensure that the power system operates securely to provide reliable, high-quality power to customers via the grid. Ancillary services are vital because power systems are complex and vulnerable, and require appropriate operational rules and control systems to ensure their operational security and stability.

According to CIGRE [4] “definitions for ancillary services can differ significantly based on who is using the terms. While some definitions emphasise the importance of ancillary services for system security and reliability, others mention the use of ancillary services to support electricity transfers from generation to load and to maintain power quality.” That distinction notwithstanding, ancillary services are usually understood as those services that are needed to ensure the power system stability as defined jointly by IEEE and CIGRE [5].

When the various definitions are translated into specific types of ancillary services, individual transmission system operators (TSOs) may include more or fewer of these specific types. This is not only because of differences in the definitions, but also partly because some of the required properties of generating plants are embedded in conventional power plants based on directly grid connected synchronous generators. TSOs of power systems with large shares of renewables, on the other hand, require new ancillary service products, because the modern installed renewable plants use power converters instead of directly connected synchronous generators.

### Types of ancillary services

The most commonly discussed and generally accepted ancillary services belong to the group known as active power reserves. These services are by nature related to the balancing described above, but whereas balancing focuses on the economic unit commitment and dispatch of individual generating plants, the purpose of reserves is to cope with imbalances that were not known when the power was traded on the day-ahead and possibly intra-day markets. Such imbalances typically occur due to errors in forecasting power demand and production; to rapid and unexpected plant shutdowns (“trips”), and to contingencies in the grid. The grid needs reserves that can respond quickly enough to cope with such unexpected imbalances.

In the past, active power reserves were categorised into primary, secondary and tertiary reserves, based on the sequence in which they were expected to operate. However, the definitions of those categories have sometimes been confused. In 2007, the European transmission system operators (ETSO) [6] introduced an alternative categorisation of active power reserves based on the process that the reserve supports. This definition distinguishes frequency containment reserves (FCRs), frequency restoration reserves (FRRs), and replacement reserves (RRs). In this section we will use these categories, with the updated definitions from the ENTSO-E glossary [7].

In Denmark, Energinet.dk has published an ancillary services strategy for 2011–2015 [8]. This strategy defines “properties required to maintain power system

stability today” as a group of services that “are required to ensure safe operation of the main power system and are not procured in the reserves market”. This group of services include short-circuit power, continuous voltage control, voltage support during faults, and inertia. All of these are addressed below.

As mentioned above, large-scale penetration of renewable power plants has also created requirements for new ancillary services products, as exemplified by Irish [9], British [10], and Texan [11] grid codes. The new services addressed in this section are fast frequency response and inertia support, synchronising power, and power oscillation damping.

### Frequency containment reserves (FCRs)

According to the ENTSO-E glossary [7] “frequency containment reserves (FCRs) means the operational reserves activated to contain system frequency after the occurrence of an imbalance.” FCRs are activated automatically as a response to frequency changes. FCRs are traditionally referred to as “primary reserves”.

FCRs were introduced as an integral part of a large WPP for the first time at the Horns Rev offshore wind farm [12] and are now a feature of many modern WPPs. However, as far as WPPs are concerned, FCRs are usually only available as “down reserve”: a reduction in supply to correct overfrequency on the grid. This is because wind power plants normally operate at their maximum possible output under the prevailing wind conditions, so they cannot provide “up reserves” to correct underfrequency when demand exceeds supply.

It is technically feasible to combine downward FCRs from WPPs with upward FCRs from flexible consumption (demand management) [13]. Another technically feasible solution is to run WPPs in such a way that they are continuously down-regulated under normal conditions, allowing output to be increased when necessary. Because this involves the non-production of wind power that is actually available, it will usually only be profitable when power prices are zero or negative. Running a WPP in down-regulated mode requires a reliable estimate of the maximum power available under the prevailing wind

conditions, so as to make sure that the plant can actually provide its quoted reserve if necessary [14].

For a power system to be secure, enough FCRs must be available to handle any unexpected events, typically within 15 minutes. Today, the required amount of FCRs is shared between the TSOs in each synchronous area; the total corresponds to the size of the largest generation unit in the area, since the sudden loss of this unit is taken as the worst case. An individual TSO in a large synchronous area typically is required to provide only a fairly small amount of FCRs.

Power system studies usually assume that wind power will not influence the amount of FCRs needed. However, recent research has shown that the planned development of offshore WPP capacity in the power systems of northern Europe will increase the need for FCRs in the medium to long term (between 2020 and 2030) [15]. This is because the predicted massive concentration of WPP capacity will cause unpredicted changes in power delivery within 15 minutes, to an extent that will sometimes exceed the amount of FCRs available at present.

The amount of extra FCRs required by 2030 to cope with offshore wind power will vary according to the weather. In calm periods, when wind production is low, the need for extra FCRs will be modest; during strong winds it could be much higher. Since making FCRs available costs the TSOs money, we recommend the development of a new way to estimate the weather-dependent need for FCRs. For much of the time, a sufficiently accurate model could save money by reducing the required amount of FCRs.

### Frequency restoration reserves (FRRs)

According to the ENTSO-E glossary [7] “frequency restoration reserves (FRRs) means the active power reserves activated to restore system frequency to the nominal frequency.” FRRs are used not just to restore the frequency following upsets, but also to correct deviations from the scheduled power flows between different TSO areas.

Usually, FRRs should be fully activated within 15 minutes. This ensures that the previously activated FCRs are restored and allows the power system to

return from an “alert” state to normal operation after 15 minutes. In traditional terminology FRR covers both “secondary reserves”, which are activated automatically, and “tertiary reserves”, which are traded on regulating power markets and thus activated manually. The term “contingency reserves” is also used [11].

The volume of FRRs needed depends on the share of wind power in the power system area. This is because the forecast errors typically increase with increased share of wind power, and FRRs are used to balance those forecast errors.

FRRs are usually provided by flexible conventional power plants, typically hydro power or gas-fired. FRRs can be imported from neighbouring power system areas if the interconnectors have sufficient capacity available. At present most power systems have enough FRRs; in northern Europe, for instance, Norwegian and Swedish hydro power provides FRRs in Denmark. In the future it will be important to maintain a flexible generation mix as wind power penetration increases, especially in electrical island power systems that are small synchronous areas such as Ireland, which cannot import FRRs.

When systems with high shares of wind power operate in conditions of high wind and low demand, economics indicate that the minimum possible number of conventional generators will be online, and that even these will operate close to their technical minimum production limits. In such cases, provided that power prices are low or even negative, it may be profitable for WPP owners to provide down-regulation FRRs. Under most conditions, however, it is not profitable to provide FRRs from wind power.

As with FCRs, providing upward FRR from WPPs is technically feasible but generally not profitable, because this would require wind energy to be spilled continuously during normal operation. Demand-side management is a much more favourable solution for upward reserves.

The EU-supported REServiceS project studied the benefits of providing reserves from renewables in



three cases representing different types of systems: the island system of Ireland [16], the “end-of-line” peninsula represented by Iberia [17], and a large north European case covering Germany, Poland, the Netherlands, Belgium, France, Great Britain, Denmark, Norway, Sweden and Finland [18]. The results clearly show that the benefits of getting services from renewables increase significantly as the penetration of renewables grows.

As an example, in Iberia, with 42% renewables, the additional annualised investment cost of making services available from renewables was estimated at €240 million/y, with corresponding benefits of approximately €660 million/y. The results also indicate that the benefits are highest in island systems (Ireland) and lowest in larger strongly interconnected systems (the north European case). The project shows that although in today’s power systems providing reserves from renewables creates very little profit; this will change in future power systems with much larger shares of renewables.

### Replacement reserves (RRs)

According to the ENTSO-E glossary [7] “replacement reserves (RRs) means the reserves used to restore/support the required level of FRRs to be prepared for additional system imbalances.” The term “regulating reserve” is also used [11].

The activation of RRs does not depend on changes in frequency or deviations from scheduled flow between power system areas, and activation times may be up to several hours.

In principle, the necessary volume of RRs depends on the level of wind power penetration in the power system area, in the same way as for FRRs. For RRs it also depends on the generation mix in the system, however, because RRs are only needed if not enough non-activated FRRs are available. If baseload generation comes from flexible hydro power plants, for example, these can provide high levels of FRRs, so there is no need for additional RRs. If the baseload units are inflexible nuclear plants, on the other hand, then the limited volume of FRRs needs to be restored by activation of RRs.

WPPs are rarely used to provide RRs. It is generally more attractive for WPPs to provide the short-term FRRs than the longer-term RRs.

### Short circuit power

Existing power systems need the service known as short circuit power to maintain voltage during momentary short circuits and ensure that protective equipment isolates the fault.

In the long term, the development of new smart protection systems has the potential to eliminate at least some of the need for short circuit power.

Short circuit power is not always explicitly mentioned as an ancillary service, because it is embedded in synchronous generators and therefore sometimes taken for granted. A synchronous generator is able to provide a short circuit current many times greater than the rated current of the generator.

Power converters connecting modern wind turbines to the grid control the amount of current entering the grid. Today it is common practice to use this control to inject a certain short circuit current during voltage dips. Yet even when they are temporarily overloaded, wind turbine converters supply significantly less short circuit power than is available from synchronous generators.

It is technically possible to provide more short circuit power from wind turbines by increasing the size of the grid-side converters, but this is not an economically sound solution. From an economic point of view it is also important to know that the need for short circuit power varies across the grid, so a general requirement for short circuit power from any generation unit will give rise to unjustified investment costs.

A more economical way to add short circuit power is to install synchronous condensers where needed. A synchronous condenser is a rotating machine that acts as an idling motor, giving control of reactive power and providing short circuit power. The Danish TSO recently installed a synchronous condenser with the main purpose of ensuring sufficient short circuit power.

Figure 24 – A possible inertia response (IR) controller in a WPP.

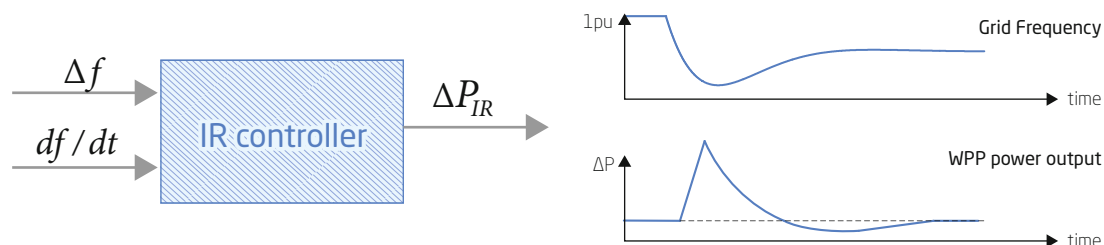


Figure 25 – Synchronising power controller in a WPP.

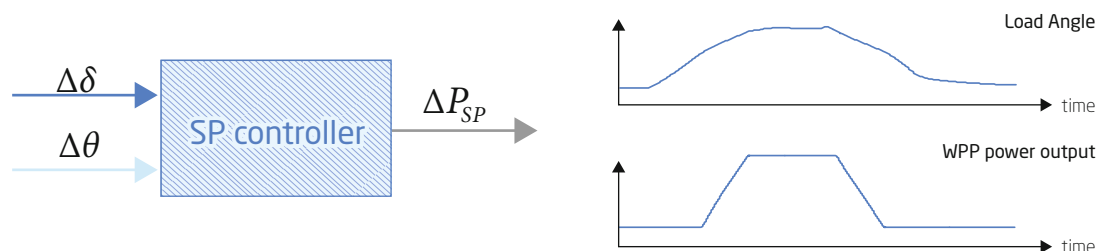
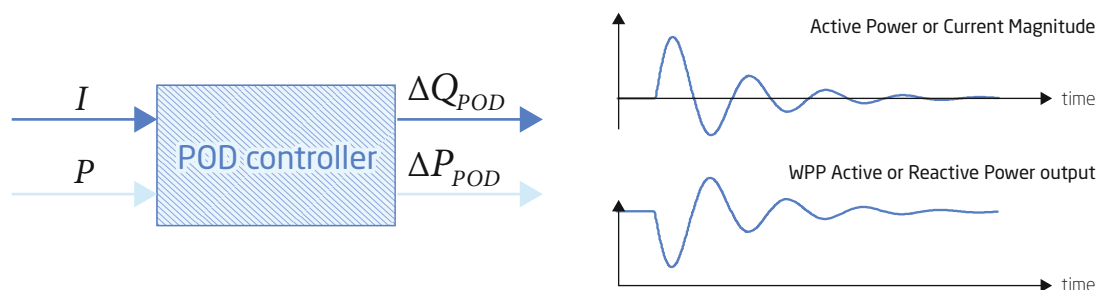


Figure 26 – A WPP can be used as a damping device to control power oscillations.



### Continuous voltage control

Voltage control is traditionally provided to the transmission grid by conventional power plants equipped with synchronous generators. Modern WPPs also provide voltage control; if the wind turbines do not have sufficient reactive power capacity to support the voltage, then auxiliary reactive power equipment is used. Shunt capacitors and static VAR compensators (svcs) are the cheapest solutions for this purpose.

Voltage control must be supplied close to where it is needed. WPPs are typically connected either to the distribution grid (onshore turbines) or to distant parts of the transmission grid, far from its

“backbone” (offshore turbines). This means that voltage support from new WPPs may not be adequate over the entire transmission grid as the share of wind power increases. Under these conditions auxiliary reactive power may be needed in the transmission grid at locations where it cannot be supplied by a generating plant. svcs will typically be the solution in such cases.

### Voltage control during faults

To prevent the voltage from dropping too low under fault conditions, the generation units need to inject reactive current into the fault. This is very similar to the need for short circuit power described above. As with short circuit power, reactive current can be



supplied by synchronous generators and, to a lesser extent, by wind turbine converters.

The first grid codes required only that wind power plants were capable of “riding through” grid faults. Most grid codes today, however, include specific requirements for the injection of current during and immediately after voltage dips. The aim is normally to ensure that enough reactive power is injected to support the voltage during the fault and immediately after it is cleared. Some grid codes, however, give higher priority to injecting active current than reactive current. This is because the TSOs in question consider frequency stability (which is controlled by active current) to be at greater risk than voltage stability (controlled by reactive current).

Where wind turbines do not have enough reactive power capacity to support the voltage, auxiliary equipment is used. Shunt capacitors and SVCs are usually not sufficient in this case, because their reactive power capacity is proportional to the square of the voltage, so it falls significantly during voltage dips. Static synchronous compensators (STATCOMs) are more suitable because their reactive power capacity is proportional to the voltage, but the technically ultimate solution is a synchronous condenser.

### Black start capability

Although TSOs have extensive plans to prevent system blackouts, it is never possible to avoid the threat completely. In the event of a blackout, the system must be restored using generation units with “black start” capabilities.

Some grid codes, such as those used in the UK [10], require black start capability from WPPs. However, most TSOs do not want to use WPPs when restoring the system after a blackout, because the restoration process is often vulnerable to fluctuations in power.

### Fast frequency response and inertia support

As the penetration of wind power increases, the inertia embedded in power systems is decreasing. Inertia is an inherent property of conventional power plants with synchronous generators, but not of renewable generators connected through electronic converters.

Lower inertia means that under sudden load increases the frequency can dip very low, possibly causing under-frequency relays to trip generation units – which of course make the problem worse.

The negative rate of change of frequency (ROCOF) can also become critically high, tripping generation units connected to the distribution network, where ROCOF relays are often used to protect against unintentional islanding. (In the long term, new intelligent islanding detection systems have the potential to replace ROCOF relays.)

The loss of inertia in the power system due to the displacement of conventional power plants by WPPs has created a need for a new ancillary service to replace it. Thanks to the fast response time of WPP controllers and the energy stored in wind turbine rotors, it is technically feasible for WPPs to provide rapid, temporary power injection to limit both frequency error and ROCOF.

Figure 24 illustrates a possible inertia response (IR) controller in a WPP. Whereas embedded inertia responds immediately to ROCOF ( $df/dt$ ), the IR controller will respond after a delay of a few line periods.<sup>7</sup> The IR controller also responds to the frequency error  $\Delta f$  in a way similar to that used by a conventional speed governor to provide FCRs. However, power injection from the WPP can only be temporary – otherwise the wind turbines would lose too much rotational speed and therefore also their aerodynamic torque.

### Synchronizing power

Synchronising power (SP) is an embedded feature of synchronous generators. It reduces the load angle between groups of synchronous generators in the power system. If the load angle becomes too high, the synchronous generators will lose torque and the system becomes unstable; at that point it needs to separate into two parts to avoid pole slipping and consequently oscillations and damage to the drive trains.

As with other types of reserves, an increase in the share of converter-connected renewable generation decreases the amount of synchronising power

7. A line period is 20 ms in a 50 Hz system.

available on the system. As a result, it may be necessary to introduce synchronising power as a new ancillary service product.

*Figure 25* illustrates a synchronising power controller in a WPP. The controller responds to changes in either the rotor angle or the voltage angle at the point of connection of the WPP.

### Power oscillation damping

Power oscillation damping is typically a feature embedded in the power system stabiliser (PSS) of synchronous generators. It damps the power oscillations in the power systems. *Figure 26* illustrates how a WPP can be used as a damping device instead for a PSS. As depicted in the figure, the oscillations in the system can be damped by modulating either active or reactive power of WPP.

### Conclusion

The largest challenges in the integration of wind energy typically arise in situations when there is high wind production, low demand, limited or inflexible trade with neighbours, and low flexibility in the other power plants connected to the system.

The solution to this balancing challenge has to be based on a mix of technical solutions and market incentives:

- To make optimal use of the wind energy potential, sufficient capacity needs to be available to export power, and transmission bottlenecks should be minimised.
- In the long term, adequate investment incentives must be provided for controllable backup power, so that sufficient capacity can be made available to the market.
- In the medium term (i.e. day-ahead), the expected ramping up and down by WPPs must be mirrored by sufficiently flexible units that can be dispatched so as to maintain the balance between production and demand.

With respect to the ancillary services provided by WPPs, the general conclusion is that there are already technically feasible solutions based on a combination

of WPPs, demand-side response and auxiliary equipment. At the end of the day, the main technical and economic challenge is to ensure that these ancillary services are provided at the lowest cost that does not compromise system security or reliability. There is a need for R&D to ensure such development of suitable technology for future wind power plants and power systems.

The solutions adopted depend very much on the individual types of ancillary services required:

- Power reserves are by far the most costly ancillary service. The need for power reserves is currently not affected by wind power, but it will increase significantly in the medium to long term as power systems acquire massive amounts of renewable energy. Wind power can and should contribute to power reserves, possibly in combination with demand-side response, but there is also a need to ensure that future power systems retain a flexible generation mix.
- Short circuit power, continuous voltage control and voltage control during faults must be provided locally. It is technically feasible and profitable to provide many of these forms of regulation from new wind power plants, but there will also be a need to install auxiliary equipment like shunt capacitors, reactors, SVCs, STATCOMs and synchronous condensers, independently of WPPs.
- Enhanced ancillary services will be needed in the future to ensure security when power systems are running with very low shares of synchronous generation. Under these conditions, power systems might otherwise lack sufficient inertia, synchronising power, and damping to prevent power oscillations.
- In the long term, the development of new smart protection systems may remove or mitigate some of the present needs for ancillary services. Replacement of existing overcurrent protection, for example, can reduce the need for short circuit power. Advanced islanding detection can replace existing ROCOF relays and thus reduce the need for very fast inertial response services.